AUTONOMOUS COTTON MODULE FORMING SYSTEM

R. G. Hardin IV, S. W. Searcy

ABSTRACT. *Cotton producers often have difficulty finding adequate labor during harvest. Module builder operators are often inexperienced and may build poorly shaped modules. Equipment manufacturers have recently introduced harvesters with on-board module building capabilities to reduce labor requirements; however, this feature is only available on picker harvesters and significantly increases purchase cost. Conventional module builders offer automatic tramping systems as an option, but these systems do not distribute cotton in the builder or prevent cotton from being pushed out of the builder by the tramper. The objective of this research was to develop an autonomous module forming system by retrofitting a conventional module builder.*

Sensors were installed on a module builder to determine the position of the carriage, tramper, and location of cotton in the module builder. An algorithm was developed to control electro-hydraulic valves so cotton was properly distributed and compressed in the module builder. The boll buggy operator could remotely control the system using a wireless display. The autonomous system constructed modules with a 64% smaller water collection area in an average time of 37.4 min. Cotton producers indicated that the system was simple to use and significantly reduced labor requirements. The autonomous system can construct quality modules and reduce labor requirements with only a small additional investment in equipment.

Keywords. *Automation, Module builder, Seed cotton, Quality, Sensors, Storage.*

A large labor force is required to operate cotton harvesters, boll buggies, and module builders during harvesting. Each harvester is typically supported by one boll buggy and module builder, both requiring an operator. An additional worker is commonly employed to collect loose cotton off the ground, cover modules, provide breaks for equipment operators, and assist with maintenance. Increasing labor costs and the difficulty in finding adequate labor have resulted in a demand for alternative harvesting systems with reduced labor requirements. Equipment manufacturers have developed systems to automatically build cotton modules on harvesters (Gola et al., 2000; Covington et al., 2003); however, these systems have several drawbacks.

Most notably, the on-board module builders are only available on picker harvesters, which use rotating spindles to remove seed cotton from the plant. During the 1994-1995 harvest season, 23% of the total volume of U.S. cotton, and 85% of Texas cotton was stripper harvested, primarily in the High Plains (Glade et al., 1996). Stripper harvesters use rotating brushes to remove the entire boll from the cotton plant. Recently, a greater proportion of cotton has been produced in traditionally stripper harvested areas – 43% of the 2009 U.S. crop was grown in Texas, Oklahoma, and Kansas (USDA-NASS, 2009). While a greater proportion of these southwestern producers are using picker harvesters, a significant amount of cotton in this region remains stripper harvested. These producers currently have no options other than using conventional module builders.

Some producers utilizing cotton pickers may find that automating existing module builders is more economical than investing in harvesters with on-board module builders. The base suggested retail price of the harvesters with on-board module builders is over $100,000 more than the comparable conventional picker harvesters (Case IH, 2010; John Deere, 2010). Retrofitting a module builder to autonomously build modules may be more economical than purchasing new harvesters with on-board module builders.

Along with reducing labor needs, an autonomous module builder would consistently build properly shaped modules that resist moisture penetration. Inexperienced workers operating module builders and the need to build modules quickly contribute to the construction of poorly shaped modules. Operator fatigue and poor visibility can also result in undesirable module shapes. One-half of surveyed modules at six gins across Texas had depressions in the top surface where water could collect (Simpson and Searcy, 2004). Simpson and Searcy (2005) examined the effect of module shape on lint quality for modules subjected to significant rainfall. Regardless of cover quality, poorly shaped modules lost an average of $200 in lint value when compared to properly crowned modules. The modules produced with an autonomous module builder also have the advantage of using existing covers and gin equipment.

OBJECTIVES

This research developed from efforts to maintain cotton quality during storage in modules. The primary goal of this

Submitted for review in August 2010 as manuscript number PM 8731; approved for publication by the Power & Machinery Division of ASABE in March 2011.

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The authors are **Robert G. Hardin IV, ASABE Member Engineer,** Research Physical Scientist, USDA-ARS, Cotton Ginning Research Unit, Stoneville, Mississippi; and **Stephen W. Searcy, ASABE Fellow,** Professor, Department of Biological and Agricultural Engineering, Texas A&M University, College Station, Texas. **Corresponding author:** Robert G. Hardin IV, USDA-ARS, Cotton Ginning Research Unit, 111 Experiment Station Rd., Stoneville, MS 38776; phone: 662-686-3096; e-mail: bobby.hardin@ars.usda.gov.

study was to develop an autonomous module forming system to reduce labor requirements during cotton harvesting while consistently building high quality modules. The main objectives of this research were:

- to develop algorithms for efficient movement of seed cotton in the module builder,
- to design a wireless communication system and boll buggy interface for control of the autonomous module forming system, and
- to evaluate the autonomous module forming system performance by measuring module shapes and recording the time required to build modules.

Literature Review

The module system of storing and handling seed cotton was developed by Wilkes and Jones (1973) in response to harvesting delays due to the unavailability of trailers. Shelby and Parish (1975) developed an automatic control system for the module builder. A basic leveling system was implemented, where the carriage was moved from the front to the rear of the module builder at a height set by the operator. This system used limit switches to detect when the carriage was at the front or rear. After this leveling pass, the compaction cycle was started. A pressure switch was used to stop a compression stroke when the maximum pressure was achieved. Time delay relays were used to control the height the tramper was retracted and the distance between tramping strokes. The automatic system continued to compress the cotton until stopped by the operator. One drawback of this system was the rudimentary leveling action, which would likely not move enough cotton; move too much cotton, causing the carriage to stall; or move a large mass of cotton to the rear of the module builder. This leveling system would also not produce a crowned surface when finishing a module. Additionally, there would be wasted action and time from raising the tramper too high or making unnecessary compaction cycles.

Commercially available systems, based on the same system described by Shelby and Parish (1975), exist for automating the compaction cycle. An additional retrofit system allows a boll buggy operator to level the cotton in the module builder (Module Automation Systems, 2009). A camera in the module builder transmits video to a monitor in the boll buggy cab, where the operator can level cotton manually or start the automatic system using a remote control. However, none of these systems automate the leveling process.

A feedback system for the module builder was developed that provided an image of the predicted module shape to aid the operator in leveling cotton (Hardin and Searcy, 2010). The system identified the maximum distance the tramper extended while compressing cotton, which had been shown to be proportional to the mass of cotton compressed and the height after compression (Hardin and Searcy, 2008). While the feedback system identified parameters needed for automation of the leveling process, no automatic control was implemented.

Materials and Methods

Specifications

The autonomous module forming system should build modules without requiring a module builder operator. The only human interaction required should be commands issued by the boll buggy operator while unloading. The minimum range needed for this bidirectional wireless communication distance between the boll buggy and module builder was 50 m (164 ft). Additionally, the autonomous system should have the capability for use with multiple boll buggies and module builders.

The sensors and software were designed to prevent undesirable functioning, regardless of operating conditions. One example of this undesirable behavior would be repetitive actions due to a sensor malfunction or programming error that would prevent the cotton from being compressed by the time the boll buggy returns to unload. Another adverse action would be pushing cotton out of the builder as the module nears completion.

The autonomous system needed to construct modules at least as fast as an experienced human operator, so that harvesting operations were not delayed. The algorithms for moving seed cotton in the module builder were designed to facilitate boll buggy unloading to ensure rapid module construction. Modules built with the autonomous system should have shapes that prevent the collection of water on their top surfaces. This condition required that the mass of cotton be greater in the center of the module builder than at the ends.

Design

The autonomous system was designed to replicate the sequence of actions an experienced human operator would use to build a properly shaped module as rapidly as possible. The module builder could not significantly compress the cotton until at least three John Deere (Moline, Ill.) 7460 stripper harvester baskets [22.9-m^3 (808-ft^3) capacity] were unloaded into the module builder. After this minimum amount of cotton was unloaded, cotton was moved towards the ends of the module builder. This action created a lower region of cotton in the center of the module to facilitate faster unloading of the boll buggy (or harvester). After the final load of cotton was placed in the module builder, cotton was moved back towards the center to produce a crowned module.

The operator cannot immediately begin leveling as the module nears completion or cotton would be pushed out of the module builder. An experienced operator will move the carriage into the cotton, extend the tramper, and move the carriage in the opposite direction of the initial movement. This sequence compresses the cotton and creates a space where loose cotton can fall. After performing this action across the entire length of the module builder, subsequent compressions will further increase the available volume for unloading cotton. The autonomous system utilized this series of actions (referred to as the quick tamp routine) to aid in unloading and preventing spillage of seed cotton. Hardware was selected to acquire the information needed to accomplish these tasks.

Hardware

The module builder used for this research was equipped with an automatic tramping system (Crustbuster/Speed King, Inc., Dodge City, Kansas). This system included a High Country Tek (Nevada City, Calif.) DVC10 valve control module that was programmed to control valve actions based on the inputs to the module. The DVC10 module had analog and digital inputs, with the ability to interface with rotational speed sensors, interpret quadrature encoders, or operate as a counter. The DVC10 had both on/off and pulse width modulation (PWM) outputs for controlling proportional valves. The DVC10 and related products were used for compatibility with the automatic tramping system.

Two additional modules, a DVC50 and a DVC70, were added to the system. The DVC50 was an expansion module providing additional inputs and outputs, while the DVC70 was a data logging module that was used for debugging and evaluating the autonomous system. These modules were connected with the DVC10 on a controller area network (CAN) bus. The CAN bus provided reliable high-speed communication between controllers using the ISO 11898 protocol. Another advantage of using a CAN-based system was that additional controllers could easily be added to the network.

Sauer-Danfoss (Ames, Iowa) PVG 32 solenoid valves controlled the carriage motor and tramper cylinder in the automatic tramping system and were also used with the autonomous system. Sensors included with the automatic tramping system were two 30-mm proximity sensors (Pepperl+Fuchs NBB10-30GM50-E2-V1, Twinsburg, Ohio) for indexing carriage position to the front or rear of the module builder and a pressure transducer (GP:50 1002-RX-2-AA, Grand Island, N.Y.) for measuring system hydraulic pressure.

An operator feedback system had been installed to provide information about the position of the carriage and the height of the module (Hardin and Searcy, 2010). The autonomous system also utilized this information. The carriage position sensing apparatus used inductive proximity sensors (Automation Direct AK1-AN-3H, Cumming, Ga.) to record rotation of the carriage drive shaft. The tramper position was determined by using an ultrasonic sensor (SensComp MINI-AE, Livonia, Mich.) to detect a target plate mounted on the tramper support column.

The autonomous system also required knowledge of the level of cotton relative to the tramper for both directing leveling actions and maximizing the speed of the compaction cycle. The ultrasonic sensor only provided the tramper position relative to the carriage. Thru-beam mode infrared photoelectric sensors (Pepperl+Fuchs ML17) were mounted on both sides of the tramper (fig. 1). Cotton blocking a beam (front or rear of the tramper) indicated that the specified side of the tramper was in contact with the cotton in the module builder. The ultrasonic sensor could then be used to determine the height of the tramper relative to the cotton surface in the module builder.

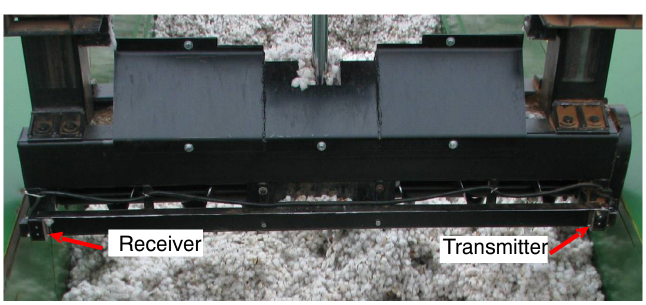

Figure 1. Tramper photoelectric sensor. This sensor pair was duplicated on the back side of the tramper.

The transmitters and receivers were mounted in housings constructed from 5.08- × 7.62-cm (2- × 3-in.) steel tubing with an acrylic cover to protect the sensors from both the applied mechanical force and cotton collecting around the sensor. The sensors were mounted on the ends of the tramper, 175 cm (69 in.) apart. This sensor had a sensing range of 20 m (66 ft); however, at the installed distance, the excess gain of the sensor was over 200. The excess gain represents the ratio of the actual received signal strength to the minimum signal strength needed to cause an output by the receiver. An excess gain of at least 50 is recommended for very dirty environments (Banner, 2003).

Sensors were needed to detect when the cotton level was high enough in the module builder that some compaction was needed before leveling. Retroreflective visible light photoelectric sensors (Banner World-Beam QS30, Minneapolis, Minn.) were mounted on all four corners of the module builder (one sensor is shown in fig. 2). Banner BRT-92 × 92 reflectors were affixed to the carriage. The excess gain was approximately four at the maximum sensing distance of 9.75 m (32 ft). These sensors were not in contact with the cotton, so the sensor faces remained cleaner, and a large excess gain was not required. Additionally, increasing the excess gain at the maximum sensing range would have required laser photoelectric sensors, which were considerably more expensive than visible light and infrared sensors.

A profile of the cotton surface after unloading was desired without having to compress the cotton. An infrared distance measuring sensor (Sharp GP2Y0A700K0F, Mahwah, N.J.) was mounted on top of the carriage and extended over the cotton in the module builder. This analog sensor had a measuring range of 100 to 550 cm (39 to 217 in.).

Wireless System and Display

Control of the autonomous system was done from the boll buggy tractor cab. The interface used was a 26.4-cm (10.4-in.) touch screen color graphic terminal (High Country Tek D210, fig. 3). Touch screen buttons were provided for the operator to start and stop the autonomous system. Additional buttons allowed the boll buggy operator to instruct the

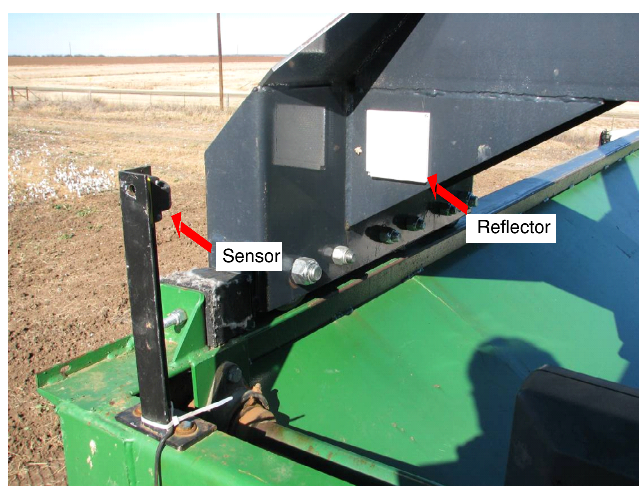

Figure 2. Photoelectric sensor and reflector for detecting cotton on sides of module builder.

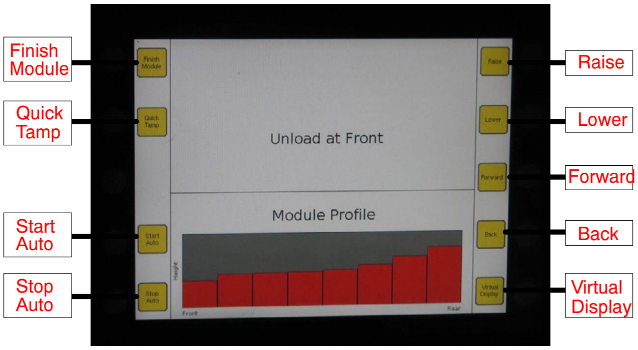

Figure 3. Autonomous system interface, mounted in boll buggy tractor cab (callouts provided to shown control button text).

module builder to quickly pack a partial buggy load while waiting to unload the remainder (referred to as the quick tamp function), to finish the module regardless of the volume of cotton in the builder, and to manually control the valves. An additional button (virtual display) provided debugging information for the prototype system. An image of the predicted module shape was displayed to guide the operator in unloading cotton. Status information was also displayed; for example, if the module builder was ready to accept more cotton.

This display was designed to be connected to a DVC10 through a serial cable. Digi (Minnetonka, Minn.) XBee-PRO 802.15.4 radio frequency (RF) modules were used in place of a serial cable and wirelessly transmitted data between the DVC10 and the display. These RF modules received serial data from the device they were connected to and transmitted a packet of data using the IEEE 802.15.4 protocol. Conversely, received RF packets were output to the connected device on the serial bus. These RF modules could form a mesh network, where any module can communicate with every other module in the network. This feature would allow multiple module builders and boll buggies to communicate in an extended version of this system. These modules were selected because of this networking capability, their low cost, ease of implementation, and maximum outdoor line-of-sight range of 1.6 km (1 mi).

The commercially available automatic tramping system contained the control hardware and some sensors needed for implementation of the autonomous module building system. Nine additional sensors, costing approximately $620, and wireless transceivers, costing $200, were also required. The terminal cost approximately $1800; however, the interface provided additional features used for testing that would not be required in a commercial system. A suitable interface could likely be purchased for less than $500.

Algorithm

The autonomous module program was implemented using High Country Tek's Intella software, a proprietary development environment used with the DVC10 modules. This software was programmed by defining various program states. The system could perform certain actions upon entering a state or would repeat a set of actions while the program remained in that state. Transitions between states were also defined, generally based on sensor values or timers.

An overview of the algorithm used to build modules is shown in figure 4. When the autonomous system was initially started, the tramper was retracted, and the carriage was moved to the front of the builder if it was not already at one end. The program was initiated with a command entered by the boll buggy operator. The operator instructed the module builder to perform the quick tamp routine or start the autonomous system. Starting the autonomous system initiated a scan of the module surface. The carriage traversed the builder and the height of the cotton was recorded at periodic intervals by the infrared distance measuring sensor.

If the average height was less than a minimum threshold, the system stopped and waited for additional loads of cotton before proceeding. With a sufficient volume of cotton in the module builder, the module profile was examined to determine if cotton needed to be moved in the module to achieve the desired shape. The preferred profile was dependent on the volume of cotton. For an average height less than the maximum threshold, more cotton should be present at the ends of the module builder than in the center to facilitate boll buggy unloading. If the average height was greater than the maximum threshold or the boll buggy operator pressed the finish button, no additional cotton would be added, so the module should have a crowned surface. An acceptable module profile resulted in five compaction cycles

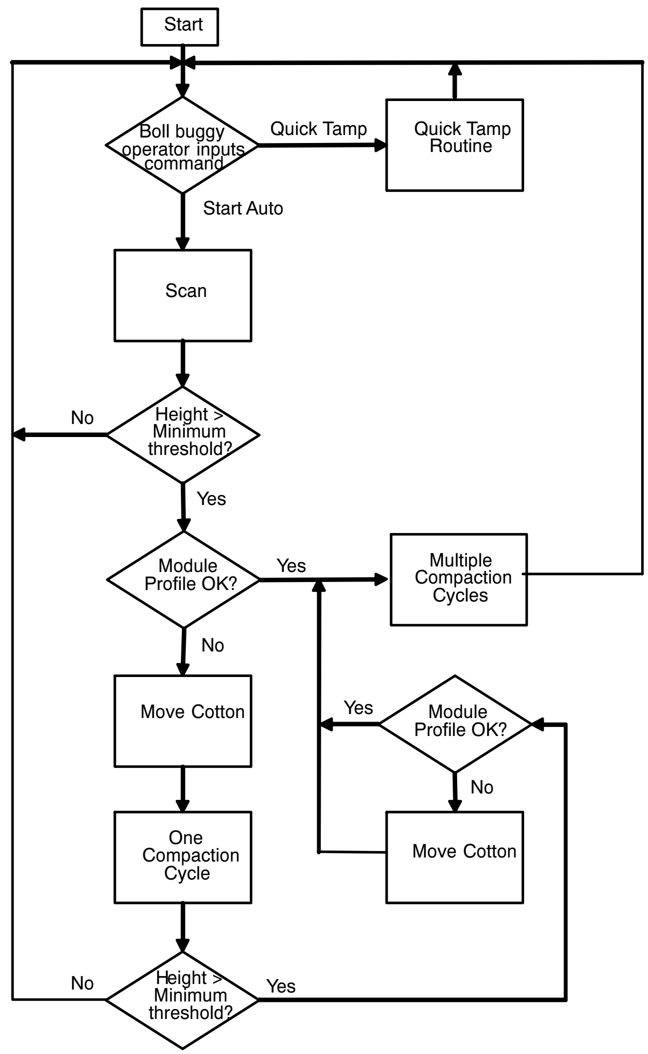

Figure 4. Autonomous system flowchart.

for an unfinished module or seven compaction cycles for the final load.

An undesirable module profile resulted in the system moving cotton towards the ends for intermediate heights or towards the center to finish the module. One compaction cycle was performed and the average height and profile were reexamined. In this step, the compressed height determined with the ultrasonic sensor was used since this measurement was a more accurate predictor of module shape. Cotton was moved one additional time, if necessary. Five compaction cycles were performed after the final cycle of moving cotton for unfinished modules and seven compaction cycles for finished modules. After the compaction cycles were finished, the system stopped with the carriage at one end and waited for another command from the boll buggy operator.

Moving Cotton to the Ends. Cotton was moved from the center to the ends in three steps at both the front and rear of the module builder. Figure 5 illustrates the sequence of movement actions taken if the carriage began the sequence at the front (left side in figure) of the module builder. Experience building modules indicated that cotton could not be pushed efficiently from the center in only one step, and three steps optimized the movement of cotton to the ends. Cotton was not pushed completely to the ends, as this resulted in modules that were higher at the ends than in the regions immediately adjacent. The steps were started one-third of the distance between the stopping point and the center, two-thirds of the distance, and at the center.

The stairstep action of the carriage and tramper did not necessarily proceed as shown, but was determined by sensor values. Each step began by moving the carriage to the desired location. The photoelectric sensors on the tramper and the ultrasonic sensor were used to lower the tramper a certain distance into the cotton. The carriage moved until the system pressure rose above a threshold specified in software. The tramper was raised a specified distance, and the carriage moved again. If the photoelectric sensors on the tramper detected that the side of the tramper in the direction of movement was not in contact with the cotton, the tramper was lowered back into the cotton before carriage movement continued.

Moving Cotton to the Center. The method of moving cotton to the center was a reversed version of the technique employed to move cotton to the end, with the same sensor package used to control movement (fig. 6). The carriage stopped short of the module builder center during each movement action as this would push cotton past the center and into the other half of the module building chamber. The starting points were one-third of the distance between the stopping point and the end, two-thirds of the distance, and the end of the module builder. After cotton had been moved on one side of the builder, the cotton was compressed (steps four and eight). Compression strokes were started at the

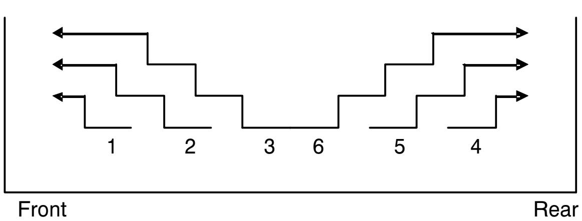

Figure 5. Sequence of actions in moving cotton to ends.

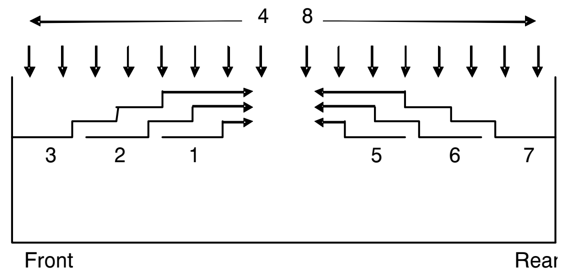

Figure 6. Sequence of actions in moving cotton to the center.

center and continued towards the end where movement of cotton had occurred. This action was added because the tramper would not clear the uncompressed cotton in the center.

Compaction Cycle. The compaction cycle was performed after moving cotton and during the quick tamp routine. A compaction cycle consisted of tramping the cotton from the starting end of the module builder to the opposite end. The tramper was extended into the cotton until the maximum pressure was detected by the pressure sensor. The tramper was retracted while the photoelectric sensor on the side of the tramper in the direction of movement was blocked by cotton. After the tramper had cleared the cotton, the tramper was raised a programmed distance above the cotton. The carriage then moved to the location of the next tramping stroke. The system was programmed to make approximately 15 tramping strokes during one pass across the module.

Quick Tamp. When unloading additional cotton on a nearly completed module, poor control of the cotton mass falling from the boll buggy into the chamber often results in cotton on the sides of the builder or overflowing onto the ground. The quick tamp function was added because it was not possible to create a large enough void in the center of the module to handle a full boll buggy basket when finishing a module. The quick tamp function also used the photoelectric sensors mounted on the tramper to determine when the tramper contacted the cotton. Simply compressing the cotton was not desirable because the tramper, even if fully retracted, pushed uncompressed cotton in the direction of movement and eventually out of the end of the module builder. The tramper was fully retracted and the carriage was moved a specified distance into the cotton. The tramper then extended a programmed distance, followed by a carriage movement in the opposite direction. Loose cotton fell into the void created by this action. The tramper was raised and this cycle repeated until the carriage reached the opposite end. One compaction cycle was then completed to create more space to unload cotton.

Cotton Detected on Sides of Module Builder. Cotton overhanging the sides of the module builder was detected by the photoelectric sensors mounted on the corners of the builder. If cotton was present on the sides of the builder during the initial scan, the system performed the same action as the quick tamp routine, although compression was not done when the carriage reached the opposite end of the module builder. If cotton was pushed onto the sides of the module builder while moving cotton to the ends or the center, the carriage was stopped. Compression strokes were done in the direction of movement until the cotton no longer blocked the photoelectric sensors. The process of moving cotton was resumed at this point.

Testing

Two cotton modules were obtained from a gin to use during the initial development of the autonomous system during the spring and early summer of 2008. These modules were repeatedly broken apart and placed in a boll buggy using a bucket loader. During this initial testing and development, sensors were installed and the basic algorithm for moving cotton was developed.

The autonomous system was first tested during harvesting on several farms near El Campo, Texas in August 2008. The quick tamp routine was added so the boll buggies could unload rapidly. Different parameter settings were tested to optimize the module shapes constructed and the speed of the autonomous system.

Continued testing was done at the Texas A&M experimental farm near College Station, Texas in September 2008. The display and wireless connection were initially used there. The system generally functioned as desired, building modules without an operator present on the module builder. However, the harvesting rate was much lower than encountered with typical commercial operations.

Additional testing of the autonomous system was performed on several farms near Anson, Texas from November 2008 to January 2009. The wireless display was installed in the boll buggy tractor cab, and boll buggy operators were instructed on the use of the autonomous system. Approximately 50 modules were built autonomously with 5 different boll buggy operators. Cotton producers in this area indicated a preference for modules with a more level top surface. By changing program parameters, the performance of the autonomous system was adjusted so the profile of cotton was always judged to be acceptable after the final boll buggy load was added. This change prevented cotton from being pushed to the center and creating a crowned shape, but demonstrated the ability of the system to meet user expectations.

A module height measurement system (Hardin, 2009) was used to record heights for 28 modules built near Anson, Texas. The autonomous system was used to build 16 of these modules. The measurement system recorded heights at multiple locations across the width of the module and was mounted on a truck, which was driven alongside the module to record heights along the length of the module. The measurement system generated a module height surface with a 15-cm (6-in.) grid spacing both laterally and longitudinally.

Evaluation

Depressions in the module height surface were identified, and parameters describing these depressions were generated. These parameters included the total depression volume, number of depressions, average depression volume, maximum depression volume, average depression depth, average depression surface area, the water collection area in a profile of average heights along the length, and the water collection area in a profile of average heights across the width. Additional details about the identification of depressions and calculation of these parameters can be found in Hardin (2009).

These parameters from analyzing the module height data were used as dependent variables in an analysis of variance (ANOVA). The ANOVA model included the forming method (autonomous or conventional) as a main effect. An additional independent effect was added to the model to distinguish modules that were measured after being covered during 22-m s^{-1} (50-mi h^{-1}) winds. While collecting data, these modules appeared to have fewer depressions; therefore, a classification variable was included to distinguish these modules. All other modules were measured before being covered. The number of modules for each combination of the two independent variables is shown in table 1. While only a small number of modules were measured after covering, the goal of this research was not to quantify the effect of covering a module in high winds on the shape of the module. The effect of the measurement condition was primarily included to produce a more accurate model and estimate of means for the forming methods.

The generalized linear models procedure in SAS (SAS Institute Inc., Cary, N.C.), *PROC GLM*, was used for the statistical analysis. An ANOVA was performed using a model with both main effects (forming method and measurement condition) and the interaction. For dependent variables with significant differences but an insignificant interaction effect, the ANOVA was performed again with only main effects. Least-squares means were calculated using the *LSMEANS* statement in SAS with the *PDIFF* option.

The times required for different actions of the autonomous system were recorded for eight modules to verify that the system could operate without increasing harvesting time. Users of the autonomous system were asked to provide their feedback regarding the speed of the system, quality of modules built, ease of operation, and interest in the system as a commercial product.

Results and Discussion

Approximately 15 modules were constructed near El Campo, Texas. The autonomous system successfully distributed cotton in the module builder and the algorithms for the quick tamp routine and moving cotton from the sides of the module builder were developed. An additional eight modules were built near College Station, Texas. The wireless system and display were initially tested, and modules were formed autonomously. Approximately 50 modules were built near Anson, Texas entirely with the autonomous system and five boll buggy operators. Height measurements and timing data were collected on these modules.

Module Shape Evaluation

The results of the ANOVA, with a full model including the effects of autonomous system use, measurement condition (before or after covering), and their interaction are shown in table 2. Significant differences between treatment combinations were observed for all three dependent variables with a

Table 1. Number of modules in each treatment group.

Treatment Combination	No. of Modules
Conventional, measured before covering	7
Conventional, measured after covering	5
Autonomous, measured before covering	14
Autonomous, measured after covering	2

Table 2. Analysis of variance table for dependent variables with a full model including all treatments and interactions.

Dependent Variable	F-Statistic	*P*-Value
Total depression volume	1.41	0.2651
Number of depressions	18.72	<0.0001
Average depression volume	0.38	0.7706
Maximum depression volume	0.64	0.5981
Average depression depth	3.77	0.0239
Average depression surface area	1.70	0.1932
Water collection area - length profile	6.52	0.0022
Water collection area - width profile	1.05	0.3886

significant ANOVA model ($p < 0.05$). The method used for forming modules (autonomous or manual) had a significant effect on the number of depressions. The least-squares means for the number of depressions per module were 43.6 when built manually, compared to 32.6 for modules formed autonomously.

While the statistical analysis indicated that the module forming method had an effect on the average depression depth, all modules measured before covering had similar average depression depths. Removing the interaction term from the model caused the ANOVA for average depression depth to be insignificant. This effect of the module forming method on the average depression depth was due to the two modules built using the autonomous system that were measured after covering. These modules had a significantly larger average depression depth than all other groups of modules because they had fewer small depressions. Movement of the cover during high winds had likely compressed the cotton and eliminated many small depressions. The small depressions that were present on modules when measured immediately after construction may have also been eliminated by movement of the cover during high winds. Furthermore, any remaining small depressions were not likely to affect cotton quality. If a good quality cover was used, wind and evaporation would likely prevent water collected in these small depressions from penetrating the cover and damaging the cotton.

The module forming method also had a significant effect on the water collection area calculated for the average height along the length. Modules built by the autonomous system had a mean water collection area of 1180 cm^2 (183 $in.^2$), significantly less than the mean area of 3270 cm^2 (507 $in.^2$) observed with modules constructed manually. A comparison of the average heights along the length of two modules built with the autonomous system and a conventionally built module are shown in figure 7 (only the top 1 m of the profile is displayed). The autonomous system produced modules that did not contain lower regions in the center, as shown by the profile of a typical module constructed by the autonomous system (fig. 7a). Even if the seed cotton was primarily unloaded on one end (fig. 7b), the module height decreased towards the opposite end. Constructing a desirable module shape with the autonomous system only required the boll buggy operator to select the finishing sequence for the final full basket of cotton and any subsequent partial loads (for

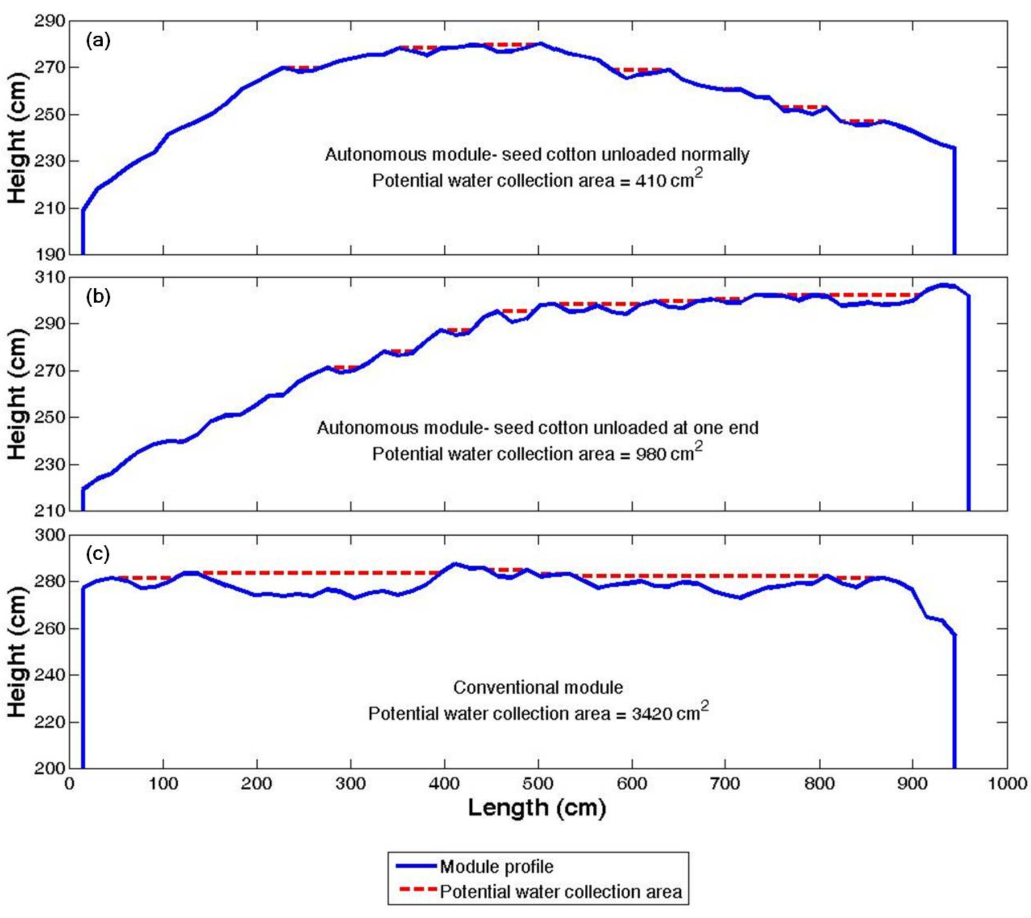

Figure 7. Average height along the length of three modules.

instance, cotton vacuumed off the ground). Some conventional modules (such as in fig. 7c) contained lower regions in the center, depending on the module builder operator's actions.

The surfaces of the modules profiled in figure 7 are displayed in figure 8. The depressions where water could collect are shown in black. The module formed autonomously with most seed cotton unloaded at one end (fig. 8b) had an extreme shape for the autonomous system, as other modules built autonomously (for example, fig. 8a) had a peak closer to the center and less variation in module heights. However, the shape of the module in figure 8b would be preferable to the shape of the module built by the human operator (fig. 8c). Since the total depression volumes and values of other parameters describing the surface depressions for the modules shown in figures 8b-c were similar, the water collection area along the length profile provided a better indicator of this difference in shapes.

Autonomous System Operating Time

Timing data for the autonomous system was collected while used with an eight-row stripper harvester, a four-row stripper harvester, and a boll buggy. When fully operational, the autonomous system did not cause any delays in harvesting, although cotton yields were generally 3.7 bales ha^{-1} (1.5 bales $acre^{-1}$) or less. Previous testing was done using the autonomous module builder with two eight-row stripper harvesters, two boll buggies, and two conventional module builders in cotton yielding over 4.9 bales ha^{-1} (2 bales $acre^{-1}$). No delay in harvesting due to the autonomous system was observed during this testing.

The user was able to select three modes of operation: normal leveling and compaction, quick tamp, or finishing the module. The mean times for each phase of operation are displayed in table 3. The normal operation average only includes passes where all leveling and compression cycles were completed, excluding data where the system stopped automatically due to a low level of cotton in the module builder or manually due to arrival of a boll buggy.

Four of the modules containing six harvester baskets had complete timing data to calculate the total time the automated system was operating. These times ranged from 34.8 to 39.5 min, with an average of 37.4 min. This figure did not include any time required to unload boll buggies. Three of these modules had the cotton delivered in four boll buggy loads. The remaining module received five boll buggy loads; however, two of these loads occurred in rapid succession and the automated system was stopped by the boll buggy operator before significant operating time elapsed. The variation in time was primarily due to the number of quick tamp routines that were performed by the boll buggy operator. Improvements to the autonomous system and an optimal pattern of

Table 3. Mean times for different autonomous system operations.

Operation	Time (s)
Normal	603
Quick tamp	136
Finishing	486

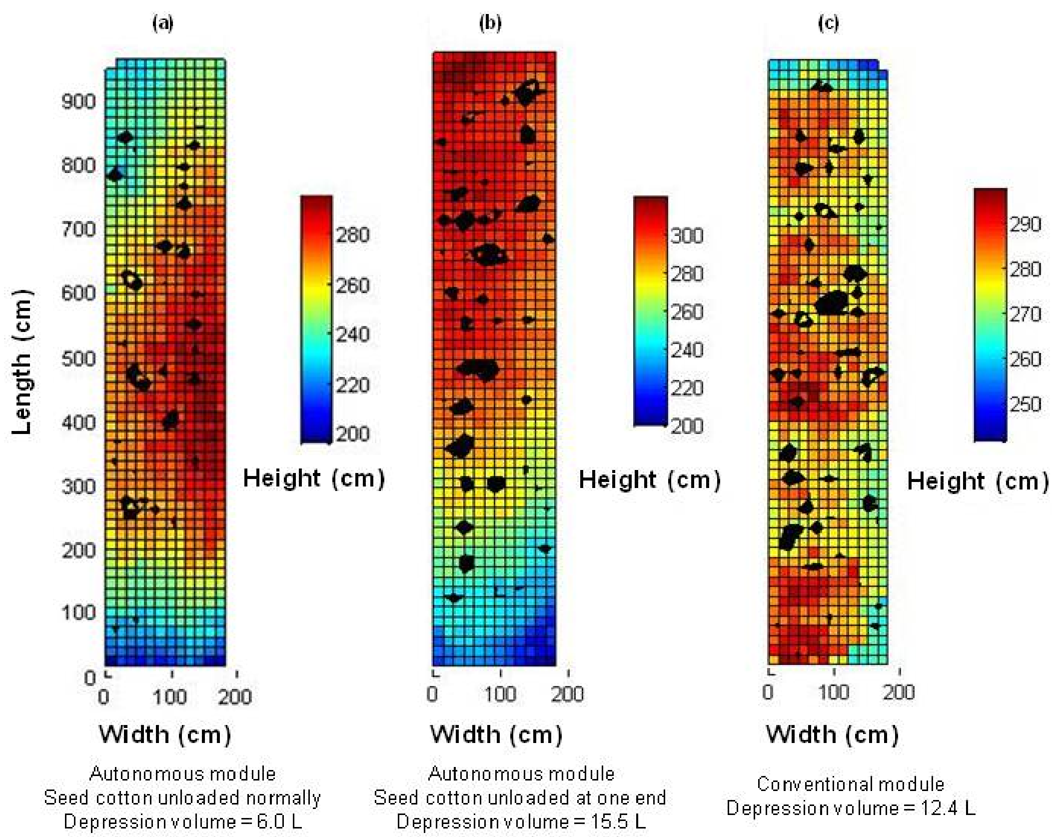

Figure 8. Surfaces of three modules with depressions displayed in black.

unloading by boll buggies could result in an expected operating times as low as 30.5 min.

The maximum yield that could be harvested without exceeding the module building rate of the autonomous system was determined. This analysis assumed that a producer had one module builder per harvester and enough boll buggies so the harvesters did not have to wait to unload. Typical field efficiencies for cotton pickers are 70% (*ASABE Standards,* 2009). Because stripper harvesters generally have similar downtimes for turning and unloading, the same field efficiency can be used. Harvesting speeds of 6.4 km h^{-1} (4.0 mi h^{-1}) for a six-row picker harvester and 6.0 km h^{-1} (3.7 mi h^{-1}) for an eight-row stripper harvester were used (John Deere, 2010).

The autonomous system operated an average of 37.4 min while building a typical module with an estimated mass of 10,000 kg (22,000 lb). An estimated 10 additional minutes were required for unloading boll buggies and moving from a finished module to the next location. Therefore, the resulting minimum time required for the autonomous system to construct a module was 47.4 min. A six-row picker harvester operating on 102-cm (40-in.) rows would harvest one typical module of seed cotton in 47.4 min if the average yield was 7.39 bales ha^{-1} (2.99 bales $acre^{-1}$) and the turnout was 35%. The yield that matched the autonomous system capacity with an eight-row stripper harvester was 5.14 bales ha^{-1} (2.08 bales $acre^{-1}$) with 30% turnout.

This estimated capacity of the autonomous system would be adequate for most producers – the average U.S. yield was 4.0 bales ha^{-1} (1.6 bales $acre^{-1}$) in 2009, while the average Texas yield was 3.4 bales ha^{-1} (1.4 bales $acre^{-1}$) (USDA-NASS, 2009). Furthermore, the estimated capacities were conservative, as 76-cm (30-in.) rows are commonly used and modules can be built larger than 10,000 kg (22,000 lb). Optimizing the autonomous system program and the unloading of boll buggies should enable the system to operate faster. For example, the second set of actions to move cotton to the end after unloading was ineffective and could be eliminated. The autonomous module forming system constructed modules as quickly as an experienced human operator; consequently, any harvest delays would be due to improperly matched machine capacities.

Autonomous System Operation

The final design functioned well, given the prototype nature of the system. The only total system failure occurred due to breakage of the cable to the photoelectric sensors on the tramper. Improved routing and protection of this cable should eliminate this problem. One cause of minor system malfunction was misalignment of the photoelectric sensors on the corners of the module builder with the reflectors on the carriage. This problem occurred twice during testing, and the sensors were subsequently realigned. A different sensing technique may be more suitable for detecting cotton on the edges of the module builder. For instance, mechanical sensors could be mounted on the carriage and output a control signal when cotton was contacted.

The photoelectric sensors on the tramper also were blocked once by soil and leaf particles that filled the housings where these sensors were mounted. Proper sealing of these housings would prevent the ingress of this material. An additional operational concern arose from an improperly sized selector valve on the module builder. When initially compressing cotton, the tramper was not raised high enough; however, this was not due to improper functioning of the autonomous system. An excessive pressure drop across the undersized selector valve caused the pressure sensor to record the maximum system pressure of 13.8 MPa (2000 psi) before the tramper was fully retracted. This high pressure reading caused retraction to stop, and loose cotton was pushed by the tramper.

The system functioned well, regardless of the location that cotton was unloaded. If the cotton was primarily unloaded at one end of the module builder, the resulting shape would be similar to the module constructed autonomously in figures 7b and 8b. This shape will prevent water collection and no effect of unloading location on operating speed was observed. No more cotton was pushed out of the module builder while operating autonomously than while operated manually by an experienced worker.

As a result of the system modification to prevent cotton from being pushed towards the center on the final pass, the location and quantity of the final load of cotton affected the final shape of the module. Generally, one full stripper harvester basket needed to be placed near the center of the module to produce a crowned shape. Furthermore, cotton unloaded at one end of a nearly finished module also posed a problem. In one instance, an eight-row stripper harvester unloaded directly into the module builder. This action required the harvester to back up beside the module builder and unload at the rear. However, this scenario would pose a problem for a human operator as well, since cotton cannot be moved from areas adjacent to the ends.

The module builder was controlled wirelessly from a maximum of 400 m (1300 ft); however, the wireless connection was generally only reliable when the boll buggy was stopped to unload at the module builder. This result was due to limitations of the architecture of the DVC system, since the DVC10 and display were not designed to be used over a wireless connection. The DVC10 controlled the display by sending large strings of data (greater than 1000 characters) over the wireless serial connection. All information displayed was resent from the DVC10 every 10 ms. Due to the large amount of information sent with no error detection and correction, one missing bit could result in the display not functioning properly. The wireless transceivers were capable of transmitting a significant portion of the messages correctly, but without any error correction, the display often malfunctioned at larger distances.

The wireless interface proved satisfactory for the initial development of the system. Reliable control of the module builder was achieved when the boll buggy was unloading next to the builder. The future extension of the autonomous system to a harvesting scenario with multiple machines will require greater range. A boll buggy will need to be directed to the appropriate module builder while in the field. Alternative boll buggy interfaces are available that should be more suited to wireless data transmission.

Acceptability of Autonomous System

Multiple boll buggy operators were trained to use the autonomous system. The simple interface with four commands was easily understood. Operators were able to use the interface after training on a limited number of modules. The major problem with this interface was that the display was not designed for wireless communication. This resulted in display errors, a lack of response to user input, and a more limited range of the wireless data transmission system. A simpler interface should function satisfactorily over a wireless serial connection. Harvesting crew supervisors commented that the system worked well and would be useful in addressing the difficulty in finding adequate labor. Module builder operators would not be needed and fewer support personnel would likely be required for an operation with multiple harvesters and module builders.

Conclusion

The autonomous module forming system was simple for the boll buggy operators to use. The algorithms for moving and compressing cotton were successful, regardless of loading conditions. Cotton could be unloaded in any reasonable manner (for instance, unloading all cotton at one end would likely not produce a desirable module) and a well-shaped module was built. The autonomous system pushed no more cotton out of the module builder while moving cotton than an experienced human operator would. The primary reliability issue was due to cable breakage, a problem that can be addressed in a commercial version by improved cable routing and protection. The wireless communication system and boll buggy operator interface functioned satisfactorily for initial prototype testing. However, this interface was not designed for wireless use, and alternative models would improve system performance.

The autonomous system built modules with more desirable shapes than a human operator. Use of the autonomous system reduced the water collection area over the length by 64%, from 3270 to 1180 cm^2 (507 to 183 $in.^2$). The mean number of depressions was decreased from 43.6 to 32.6. If the load completing the module contained at least one harvester basket of cotton, modules built with the autonomous system did not have any low regions when viewed from the side. When the load finishing the module consisted of a partial basket, a desirable module shape was constructed by the boll buggy operator selecting the finish command for the final full basket and the final load containing a small amount of cotton. The time required to build modules with the autonomous system, 37 min, was comparable to the time needed for an experienced human operator to build a module. No delays in harvesting operations due to the autonomous module builder were observed.

The autonomous module forming system was installed on an existing module builder with an automatic tramping system; consequently, the additional equipment costs for the prototype were small. The autonomous system eliminated the need for a module builder operator and constructed modules with more desirable shapes.

Future Development

The Texas A&M System Office of Technology Commercialization has pursued patent protection on the autonomous module builder. This invention has been licensed to Crustbuster/Speed King, Inc. for commercial development. A commercial system should be available on new module builders for the 2011 cotton harvest, with a cost not significantly exceeding a module builder with an automatic tramping system.

Acknowledgements

This research was supported by Crustbuster/Speed King, Inc. and Texas AgriLife Research. The authors are grateful for the assistance of many Texas cotton producers and ginners in testing and evaluating this system and the technical support provided by High Country Tek during software development.

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